Cassini's Grand Finale – Attitude Control Subsystem Performance During Proximal Ring Plane Crossings

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On April 22nd, 2017, the Cassini spacecraft made its final close targeted flyby of Titan, placing Cassini in the gap between Saturn and its innermost D-ring for the first time ever of its mission at Saturn. Cassini proceeded to fly through this region 22 times, and on September 15th, 2017, Cassini plunged into Saturn's atmosphere, concluding a remarkable, nearly 20-year mission. The attitude control subsystem performance during these 22 "proximal" orbits exceeded expectations. Prior to the proximal orbits mission, the effects of dust hazards, Saturn atmospheric drag torque on Cassini's control authority, radiation on the sensitive instruments, bright body interferences to the star tracker, pointing discrepancies caused by trajectory deviations, and possible fault protection scenarios were assessed. This paper discusses the results of these risks experienced by the attitude control subsystem over the proximal orbits mission, any interesting telemetry observed, as well as any last minute procedural changes implemented along the way.

Nomenclature

AACS	=	Attitude and Articulation Control Subsystem
AFC	=	Attitude Control Flight Computer
CDA	=	Cosmic Dust Analyzer
DBE	=	Double Bit Errors
HGA	=	High Gain Antenna
HRG	=	Hemispheric Resonator Gyroscope
IRU	=	Inertial Reference Unit
LOS	=	Loss of Signal
MIMI	=	Magnetosphere Imaging Instrument
mrad/s	=	Milliradians per second
NASA	=	National Aeronautics and Space Administration
PDT	=	Pacific Daylight Savings Time
RCS	=	Reaction Control System
RPC	=	Ring-Plane Crossing
rpm	=	Revolutions Per Minute
RPWS	=	Radio and Plasma Wave Spectrometer
R_S	=	Radius of Saturn
RTG	=	Radioisotope Thermoelectric Generator
RWA	=	Reaction Wheel Assembly
SBE	=	Single Bit Errors
SET	=	Single Event Transients
SID	=	Star identification
SOI	=	Saturn Orbit Insertion
SRU	=	Stellar Reference Unit
SSA	=	Sun Sensor Assembly
SSR	=	Solid State Recorders
UVIS	=	Ultraviolet Imaging Spectrograph

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I. Introduction

On September 15th, 2017 at 4:55:43 am Pacific Daylight Savings Time (PDT), the last S-Band carrier signal of the Cassini spacecraft was received on Earth at the Jet Propulsion Laboratory, thereby concluding a 20-year long mission. Launched on October 15, 1997 from Cape Canaveral Air Force Station atop a Titan 4B launch vehicle, the Cassini spacecraft reached Saturn on June 30, 2004 after a 6.7-year cruise, during Saturn's early winter season over the Northern hemisphere (see Figure 1). The first four years of Cassini's exploration of Saturn was called the "Prime Mission", spanning from June 2004 through mid-2008. The Prime Mission consisted of the Huygens probe release onto Saturn's giant moon Titan on January 14, 2005, 45 close flybys of Titans, and 4 flybys of the icy moon Enceladus. Other major discoveries also made during this phase of the mission included Saturn's polar storms and propeller-like formations in the rings of Saturn. The second phase of Cassini's exploration of Saturn was called the "Equinox Mission", spanning mid-2008 through September 2010. The "Equinox Mission" was so named because, in mid-2009, the rays of the Sun became exactly parallel to the ring-plane (vernal equinox), allowing new observations of the rings to be made. During the Equinox Mission, Cassini performed 28 additional flybys of Titan and 8 of Enceladus, including one which Cassini made the closest ever approach to Titan at only 880-kilometer (km) altitude. An extended-extended mission, called "Solstice Mission" was granted to the Cassini mission that spanned from September 2010 through September 2017. The "Solstice Mission" was named to denote the Saturn season change from Spring to Summer over the Northern hemisphere in May of 2017. This phase of the mission consisted of 56 additional Titan flybys and 11 more low-altitude Enceladus flybys. It also included the final phase of the Cassini mission – the "Grand Finale", during which the Cassini spacecraft crossed over Saturn's equator 22 times in between Saturn and its innermost D-ring for the very first time of any flight missions, before plunging into the Saturn atmosphere.

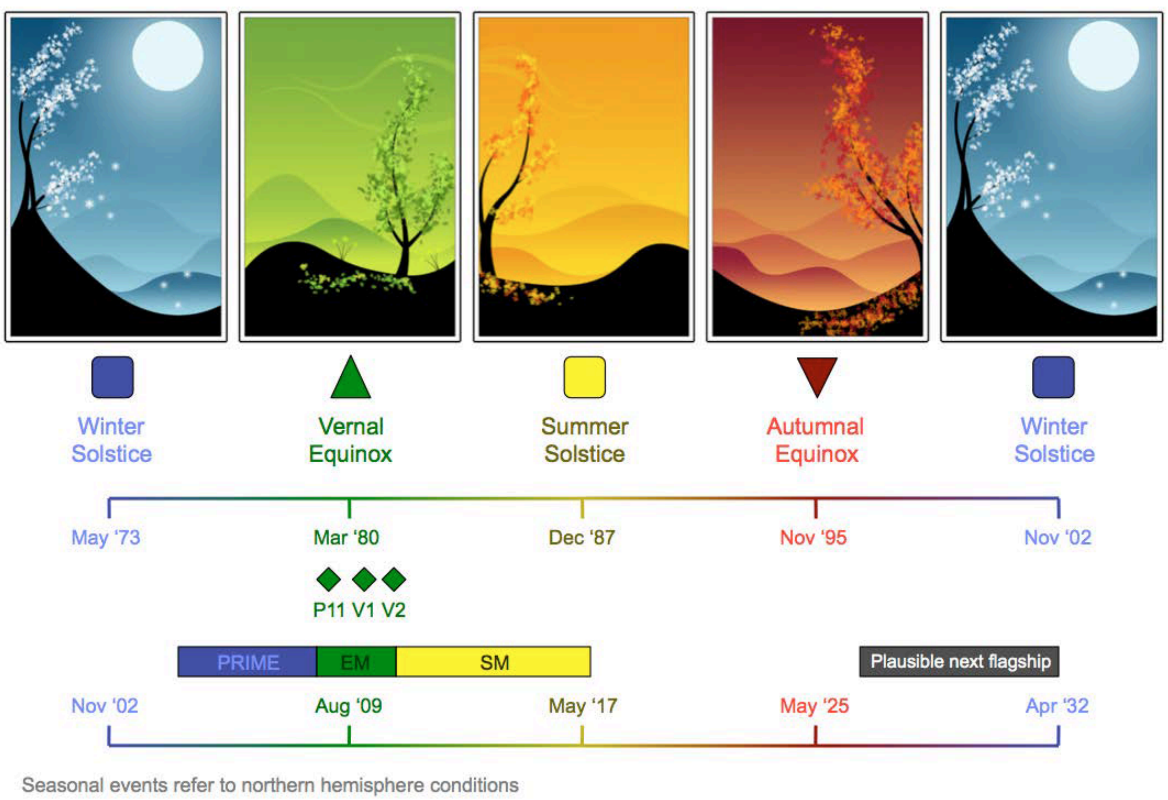

Figure 1. Saturn's seasonal timeline. Cassini had 3 phases of mission at Saturn: Prime, Equinox, and Solstice mission. Prior to Cassini, Pioneer 11, Voyager 1, and Voyager 2 also performed Saturn flybys.[1]

Cassini's final fate was conceived in 2008 after many decommission options were considered. Due to NASA planetary protection requirements, the plan had to ensure that Cassini could not accidentally impact Saturn's moons, including Titan and Enceladus, thus preventing contamination of these sensitive environments that may provide clues to formation of microbial life. Feasible options included sending Cassini to survey the "ice giant" planets –

Uranus and Neptune, neither of which have been closely visited by a spacecraft since Voyager 2 in the 1980s. Alternatively, Cassini could have been dispatched to investigate a few of the Centaurs, large comet-core-like bodies inhabiting the regions between the orbits of Jupiter and Uranus. Cassini could also have been directed back inward to explore Jupiter, extending the early investigation done by the Galileo spacecraft from 1995-2003 before it was deorbited into Jupiter's atmosphere. Even at Saturn, options were available to put Cassini into a stable long-term orbit with statistical certainty of no possible impacts for at least 500 years of flight. Or, Cassini could be placed into an impact trajectory into Saturn's atmosphere (similar to the decommissioning plan of Galileo), thereby satisfying the planetary protection requirements while also providing rare opportunities for Cassini to provide answers to questions that remained puzzling to the scientific community even after nearly two decades at Saturn. By flying in between Saturn's innermost D-ring and grazing through Saturn's atmosphere, more precise magnetic field measurements could be made to better understand Saturn's rotation rate, direct analysis of Saturn's atmospheric composition could be collected, and direct sampling of the dust particles from the rings structures could be obtained. This unprecedented opportunity was too exciting to pass up, and the "proximal mission" design of the Grand Finale was born.

Early end-of-mission trajectory studies showed that, from a high-inclination orbit with an orbital period of roughly 7 days, a Titan gravity assist could be utilized to jump over the rings of Saturn and place Cassini on a ballistic trajectory with a Saturn impact end-point.[2] Furthermore, this unique design allowed Cassini to fly in between Saturn and its innermost ring for *multiple* orbits prior to the Saturn impact. Titan had been an anchor for the entire Cassini mission design at Saturn. A single Titan gravity assist could provide over 800 m/s of trajectory change ΔV, which is a tremendous amount comparing to Cassini's propulsion system, which had only 160 m/s ΔV capability remaining for the entire 7-year Solstice mission.[1] The Titan flybys allowed Cassini to repeatedly change orbits throughout the mission at Saturn, enabling its many diverse scientific discoveries. The same strategy was implemented to allow for the proximal orbit mission. The proximal orbit design was constructed to allow for 22 orbits over a 5-month period with Cassini passing through periapsis inside the rings, starting from one very last close Titan flyby on April 22nd, 2017. This was the 126th Titan targeted flyby at an altitude of 979 km. Prior to this, a close Titan flyby in late 2016 first brought the spacecraft periapsis from 3.6 Saturn radii (R_s) to 2.5 R_s, and placed Cassini periapsis crossings in between the Saturn F-ring and G-ring. These 20 high inclination (63.8 degrees) F-ring orbits from late November 2016 to mid-April 2017 prepared Cassini for the final Titan 126th flyby, where Cassini's periapsis was further reduced from 2.5 R_s to 1.06 R_s. From that point on, Cassini was on a completely ballistic trajectory, set to impact Saturn on September 15th, 2017 after 22 proximal orbits with periapsides just above the Saturn cloud tops (Figure 2).

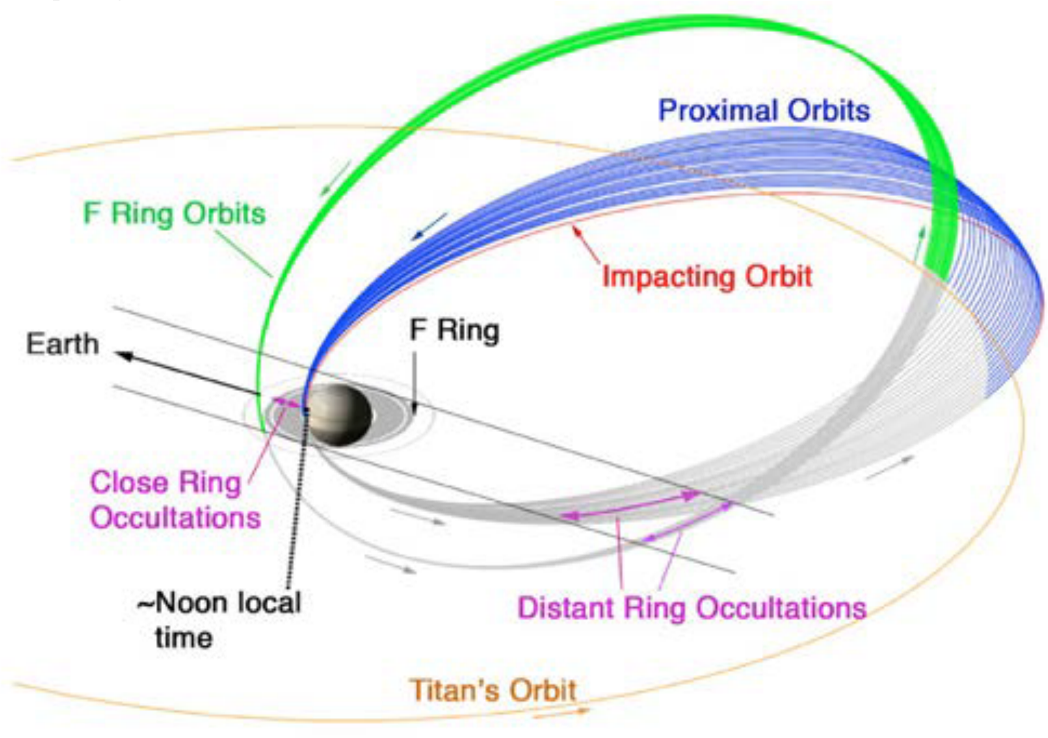

Figure 2. The "Grand Finale" mission included 20 F-ring orbits and 22 proximal orbits prior to plunge.[1]

Each of the periapsis crossings during the proximal orbit mission occurred on the sunlit side of Saturn at various altitudes, with Cassini gliding down from Saturn's Northern hemisphere towards the Southern hemisphere. The equatorial radius of Saturn (1 R_s) from Saturn center to the 1-bar atmospheric density is estimated to be roughly 60,268 km. It was also estimated that within 1,300 km above this 1-bar atmosphere region, at around 61,500 km from Saturn center, the Cassini spacecraft would tumble due to effects from atmospheric drag torques (see Figure 3). Between 62,000 and 65,000 km, a 3,000-km wide "clear zone" was expected to exist just inside the inner edge of the D-ring. The altitudes of the proximal orbit periapsis crossings were carefully designed so that scientists had opportunities to sample both the ring particles as well as the Saturn atmosphere, without risking the health of the spacecraft prior to the final plunge. While this gap was predicted by scientific models to be a benign region for dust hazards, caution was exercised as Cassini had never before explored this region of the Saturnian system. The mission planners along with the science instrument teams came up with the following strategy for the 22 proximal orbit observations. The first 5 orbits were designed for each of the periapsis crossings to occur in the middle of the 3,000-km wide clear zone. The next 7 orbits put Cassini higher closer to the edge of the D-ring to allow better sampling of the D-ring environment. Another 5 orbits placed Cassini back towards the middle of the 3,000-km safe region. The final 5 orbits prior to the plunge were designed to graze the Saturn atmosphere at just over 1,600 km above the 1-bar atmospheric "surface".

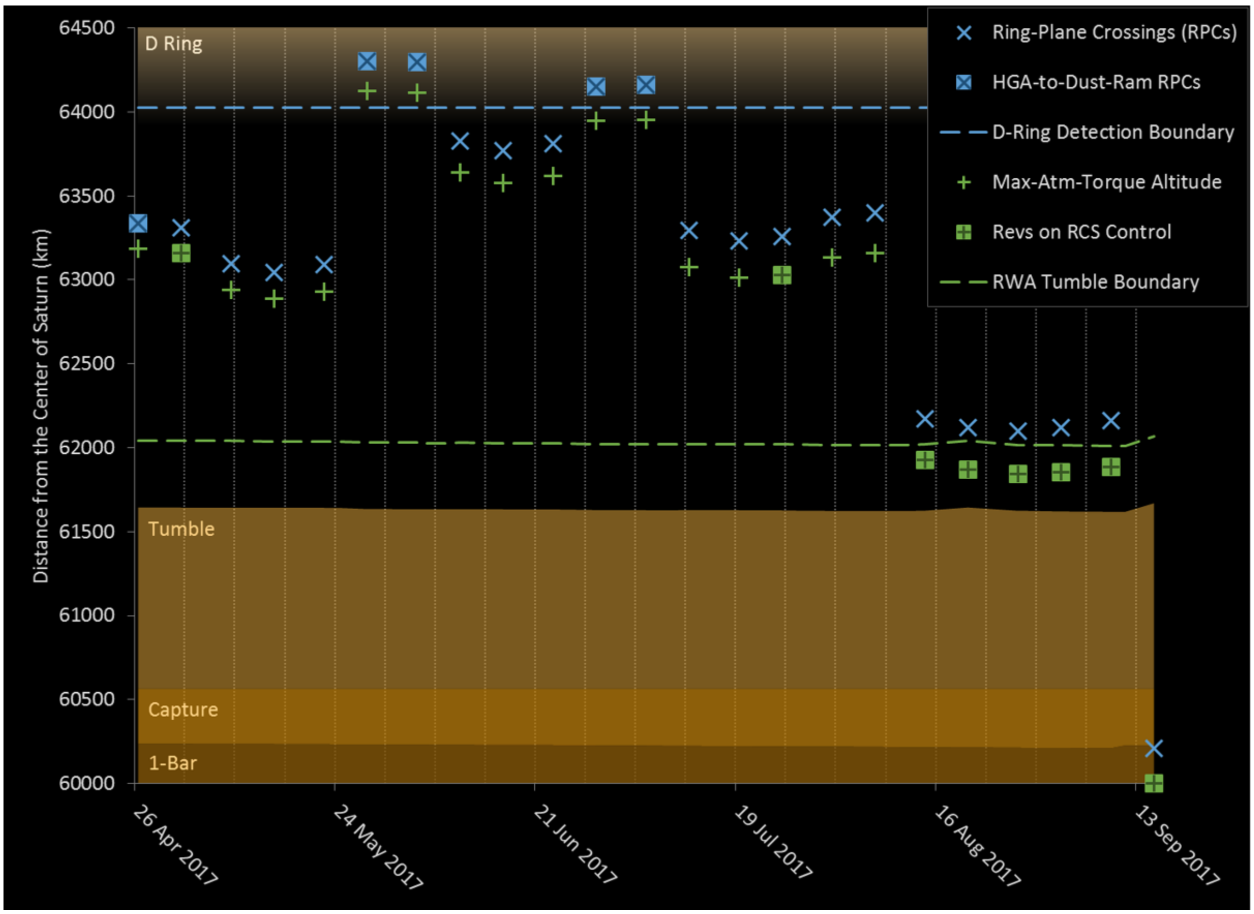

Figure 3. Cassini's flyby altitudes for each of the 22 proximal orbits. (Courtesy of Erick Sturm, Jet Propulsion Laboratory)

The strategy employed for the proximal orbit design not only allowed for various scientific measurements to be made, but it also allowed engineers to have time to assess the risks of this newly explored region throughout the operations of each of the 22 proximal orbits. The dust environment was not the only item that required real-time assessment. Spacecraft controllability, Saturn radiation effects on the sensitive instruments like the Inertial Reference Unit (IRU) and the Solid State Recorders (SSR), bright bodies like Saturn and the rings interference on the Stellar Reference Unit's (SRU) ability to track stars, and trajectory deviations for the periapsis crossings all needed to be carefully monitored and reviewed. It was crucial for the attitude control engineers to rapidly analyze telemetry from each proximal orbit crossing to ensure the safety of the Cassini spacecraft to the end, and to determine whether the telemetry matched the expected models. This paper discusses the strategies the attitude control team implemented during the planning and design phases prior to the proximal orbit mission, the expected environmental conditions and spacecraft responses, and the attitude control subsystem performance during the proximal ring plane crossings. Unexpected results from the telemetry and last-minute design changes are also discussed in this paper.

II. Cassini Attitude Control Hardware

Cassini was a 3-axis stabilized spacecraft with an 11-meter magnetometer boom and three 10-meter Radio and Plasma Wave Science antennas. A body-fixed 4-meter diameter High Gain Antenna (HGA) parabolic reflector dish was used for telecommunications. Data was recorded on two 2-Gbit Solid State Recorders and played back to Earth every day or two. The spacecraft was powered by three Radioisotope Thermoelectric Generators (RTG) that produced a total of 885 Watts at launch but were producing about 603 Watts of power by the end of mission. There were 12 science instruments on board the Cassini spacecraft, nearly all of which had fixed orientations. To point a science instrument at an object of interest, the whole spacecraft had to be slewed to achieve the desired pointing.

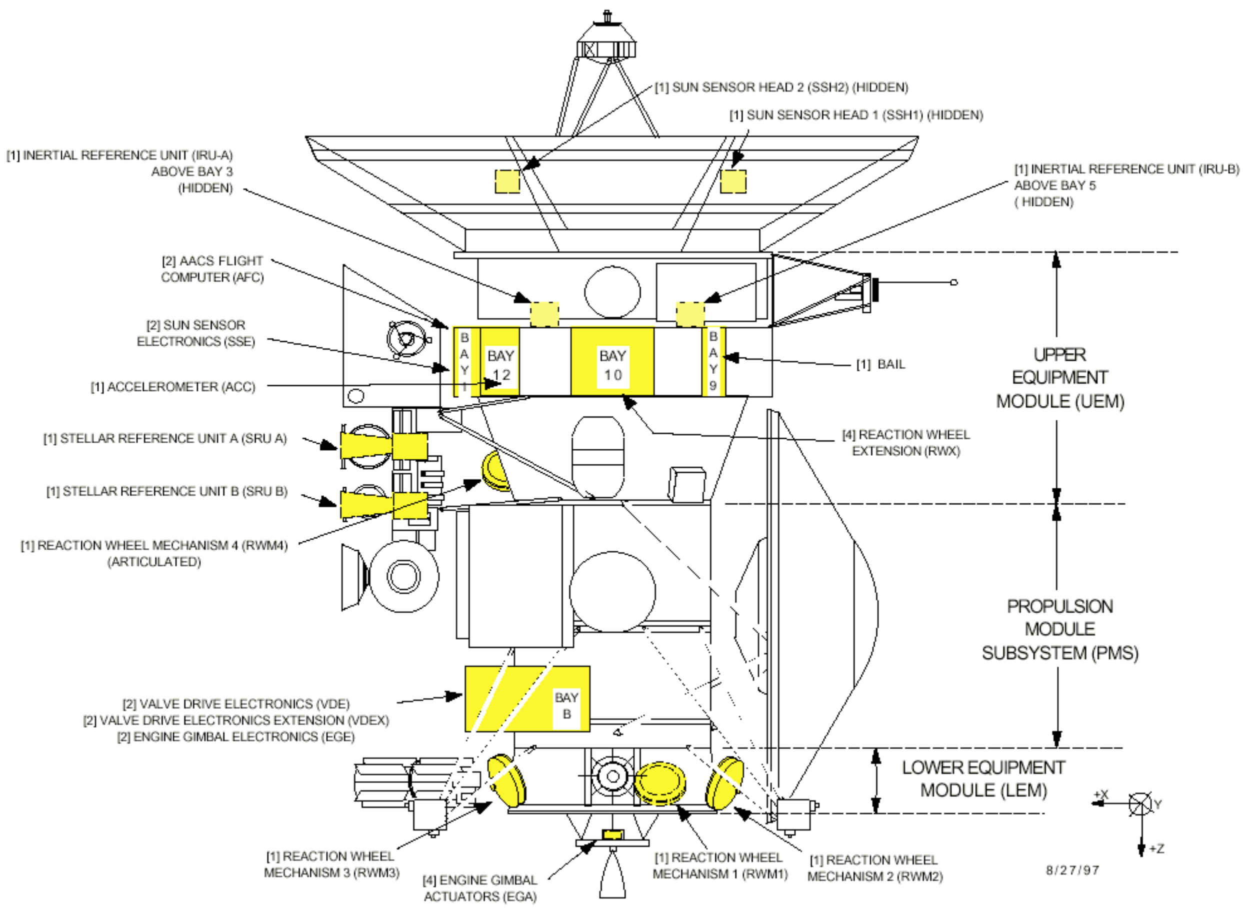

Figure 4. Cassini spacecraft diagram showing AACS hardware.[3] For clarify, the multi-layer insulation and the main engine cover were removed in the figure.

There were three key sensors in the Cassini Attitude and Articulation Control Subsystem (AACS) onboard the spacecraft that worked together to establish the attitude knowledge: the Inertial Reference Unit (IRU), the Stellar Reference Unit (SRU), and, during initialization, the Sun Sensor Assembly (SSA).[3] Two IRUs were mounted on the inner -Y side of the Cassini spacecraft body frame, two SRUs were mounted on the outer +X side with its optics pointed along the spacecraft +X direction, and two SSAs were mounted on the -Z side of the spacecraft inside the HGA dish (see Figure 4).[4] Each IRUs contained four Hemispheric Resonator Gyroscopes (HRG). Three orthogonal HRG units were used as prime inertial sensors while the fourth skew-oriented gyroscope was used as a "parity checker". The IRU obtained and supplied the spacecraft attitude change data to the Attitude Control Flight Computer (AFC), and the AFC flight software filtered this data into spacecraft body-rate and the 3-axis inertial attitude knowledge was updated. IRU scale factor errors and misalignment could induce attitude knowledge errors over time if not corrected by star tracker celestial updates, and therefore Cassini attitude determination nominally used a SRU as the prime sensor, supplemented with IRU measurements in between star updates. Each SRU had an optical field-of-view of ±7.5 by ±7.5 degrees (a square 15 degrees across) and three-axis attitude reference was determined based on star data from two to five stars in the SRU's field-of-view. The straylight field-of-view of the SRU was a 30-degree radius cone. Valid star identification (SID) could be suspended up to 5 hours if Saturn, the rings, or other bright bodies (i.e. Saturn's satellites) entered the SRU's straylight field-of-view. During this time, attitude estimation used IRU-only attitude propagation. In situations when the spacecraft attitude was completely lost due to anomalies, the spacecraft would first perform a sun search with the SSA before acquiring 3-axis stellar reference with star identification.

Cassini's propulsion system included a monopropellant thruster based Reaction Control System (RCS) and a bipropellant (Nitrogen tetroxide/Monomethylhydrazine) main engine system. The monopropellant system had eight prime and eight backup 0.9 Newton (N) hydrazine thrusters used for small (< 0.3 m/s) ΔV maneuvers, low altitude Titan flybys, and momentum dump "biases" for the Reaction Wheel Assemblies (RWA), while the main engine consisted of a prime and a backup 445 N system that was used for large (> 0.3 m/s) ΔV maneuvers.[1] The prime RCS system had 4 thrusters that fired parallel to the spacecraft body -Z-axis, one on each of the four thruster clusters (see Figure 5). These Z thrusters were used for Z-axis translational ΔV maneuvers as well as attitude control about the spacecraft ±X and ±Y body axis. There were four additional thrusters that fire as couples parallel to the spacecraft Y body axis for attitude control about the spacecraft Z-axis. The thruster force magnitudes and moment arms were such that RCS control torques of 1 to 2 Nm were provided about each spacecraft body axis from the RCS system.

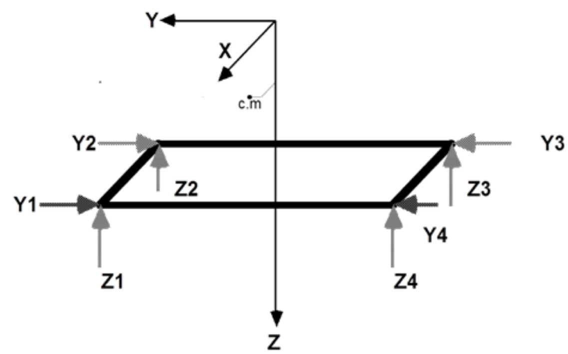

Figure 5. Cassini Thruster Configuration.[3]

The Reaction Wheel Assemblies provided more precise and stable pointing than the RCS system, and helped conserve hydrazine propellant for the duration of the mission. Cassini had three RWAs forming an orthogonal set fixed in the spacecraft body frame, and a fourth articulable RWA as a backup. Each RWA had a 34 Nms momentum storage capability and provided motor torque of 0.165 Nm.[1] The articulable backup RWA had been actively in use in the control loop since July of 2003 while one of the three body-fixed RWAs was powered off. For the vast majority of the mission at Saturn, Cassini was on RWA control except for momentum dump "bias" events and times where RWA control authority was not sufficient, such as during low altitude Titan flybys where large external atmospheric drag torque needed to be accounted for.

III. Dust Hazard Mitigation

Prior to the proximal orbits mission, Cassini was never intended to penetrate the main rings of Saturn (A, B, and C rings) or the divisions within these ring bands (Figure 6) due to risk of hypervelocity impacts caused by dense materials in these rings. However, Cassini had on many occasions since arriving at Saturn passed through outer rings above the Roche limit located at 2.44 R_s, the limit within which bodies of material tend towards breakup and ring formation, and beyond which bodies of material tend to coalesce to form moons (Figure 7).[5] Cassini's ring plane crossings started with Saturn Orbit Insertion (SOI), where Cassini crossed in between the outer edge of the main rings and the G-ring. This crossing radius was chosen only after extensive studies were done on past dust hazard experiences provided by previous missions, Pioneer 11 and Voyager 2. These spacecraft actually flew through a rather dense portion of Saturn's G-ring and Cassini was carefully targeted to just miss this dense region. The location chosen for SOI had the advantage of not only being close enough to Saturn so as not to incur a higher propellant cost for a more distant orbit insertion, but also avoided the orbits of both Janus/Epimetheus and Mimas, as well as the G-ring. Nonetheless, in order to take all possible precautions for the orbit insertion, a risk mitigation strategy was implemented in which the Cassini spacecraft was commanded to point its large HGA dish towards the direction of flight (where the dust stream, or RAM, direction would be relative to the Cassini spacecraft). This allowed the HGA to shield the rest of the sensitive science instruments and engineering hardware mounted on the spacecraft bus from dust impacts. The wavelengths used by telecommunications, radar, and radio science were long enough that the high gain antenna (HGA) was relatively insensitive to impacts of millimeter-sized or smaller particles which dominate particle distributions in the less-dense rings. Along with closing the accordion-like clamshell main engine cover, using the HGA-to-RAM attitude became standard practice for high-risk dust hazard ring plane crossing events.[1]

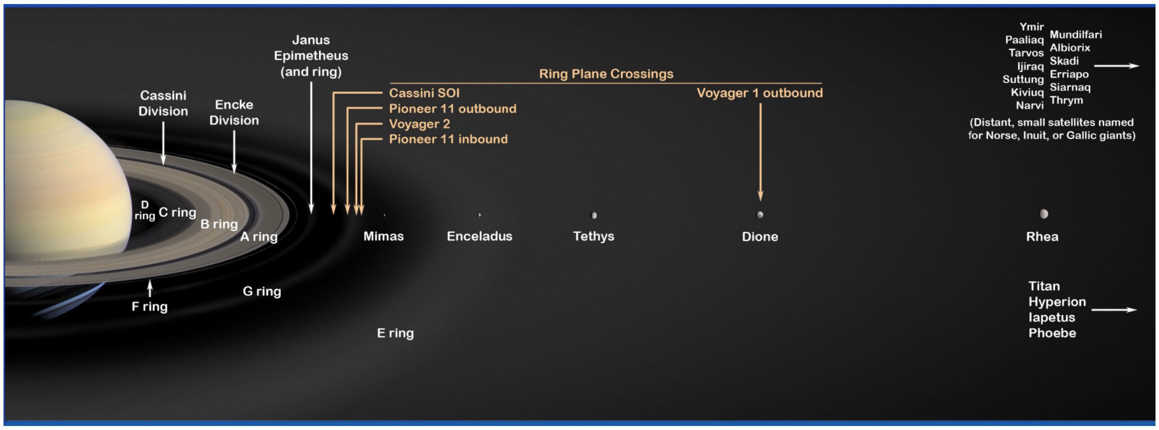

Figure 6. The rings of Saturn.

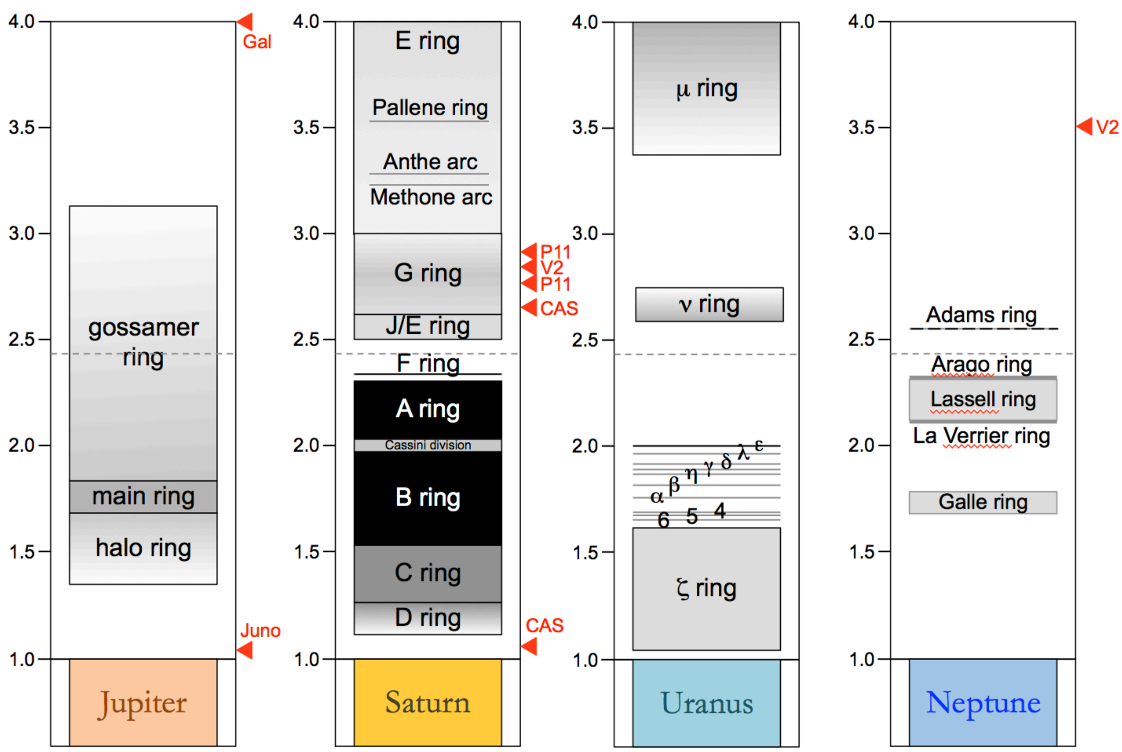

Figure 7. Various ring systems of the outer planets plotted in distance in planetary radii from the planet center. The figure shows various ring plane crossings of the outer planets performed by flight missions (i.e. Galileo, Juno, Pioneer 11, Voyager 2, and Cassini). Dashed lines depict the Roche limit.[5]

The HGA-to-RAM pointing strategy was used not only during the SOI ring plane crossings but also during repeated ring plane crossings near the G-ring throughout Cassini's mission at Saturn. The dates for these ring plane crossing events and the intercepting ring regions are provided in Figure 8. Therefore, this dust hazard mitigation procedure had been well established prior to the proximal orbits mission, and was expected to be sufficient for the Grand Finale as well. In addition, each Critical Ring Plane crossing event throughout the mission provided further data for the scientists to better characterize the ring dust environment in preparation for the proximal orbit mission. Ring models were developed to estimate the hazards of crossings through Saturn's faint rings with data obtained from Cassini's science instruments – the Cosmic Dust Analyzer, the Imaging Science Subsystem, the Visual and Infrared Mapping Spectrometer, and the Radio and Plasma Wave Spectrometer. These measurements and the resulting model continued to indicate that a 3,000-km safe zone exists between the inner-edge of the D-ring and Saturn's upper atmosphere. The combination of the updated dust hazard model and the well-established operational risk mitigation strategy gave the Cassini operations team confidence in executing the proximal orbit periapsis crossings.

Critical Ring Plane Crossings	
Ring Regions*	Date
G	7/1/04
JE	7/1/04
JE	7/1/04
G	7/1/04
E	3/9/05
G	4/14/05
E	9/23/05
G	6/11/07
G	6/28/07
JE	6/28/07
G	1/27/10
G	2/13/10
G	6/19/10
JE	11/24/15
JE	12/6/15
JE	12/11/16
JE	1/2/17
D	4/26/17
D	5/28/17
D	6/4/17
D	6/29/17
D	7/6/17

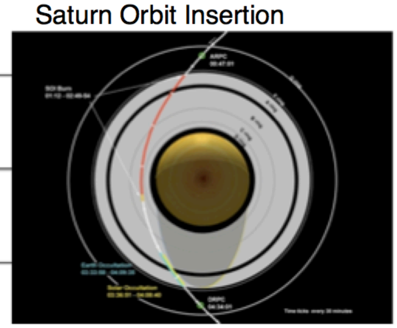

Figure 8. Critical Ring Plane Crossing events conducted by the Cassini spacecraft. Each of these events was executed with HGA-to-RAM as the primary pointing for the spacecraft attitude.

The risk-mitigation strategy implemented for the proximal orbit mission commanded Cassini's spacecraft attitude to point HGA-to-RAM for the first proximal orbit periapsis crossing, in case the dust modeling was proven to be inaccurate. The 6th, 7th, 11th, and 12th periapsis crossing events, in which Cassini was to fly closer to the D-ring (Figure 3), were also designed with the HGA-to-RAM attitude during periapsis crossings, since risk of dust impacts was higher for these orbits. The other periapsis crossings were designed in the background sequence to utilize science observation favorable attitudes. Background sequences were lists of commands uplinked to the spacecraft so the spacecraft would autonomously execute them at the specified times. However, *contingency* sequences were built for all of the remaining 17 periapsis crossing events that could be implemented at the last minute to command the spacecraft to abandon the background sequence science attitude, turn to the HGA-to-RAM attitude, and then return back to the background sequence configurations once ring plane crossings occurred. The results of the first proximal orbit periapsis crossing was crucial in the decision of implementing contingency sequences. If the first periapsis crossing showed higher dust than originally anticipated, the Cassini team may have chosen to abandon the science favorable attitudes for subsequent periapsis crossings and reorient itself to the risk-mitigation attitude, HGA-to-RAM.

On April 26, 2017, Cassini made its first dive through the gap between Saturn's upper atmosphere and its innermost D-ring. The results proved to be even more favorable for spacecraft safety than predicted in the dust model. The dust environment was so benign that the Cassini Project Manager called it "The Big Empty". The data from the Radio and Plasma Wave Spectrometer (RPWS) instrument showed that the dust environment in between the Saturn's upper atmosphere and its innermost D-ring was less than observed even at the F-ring crossings in late 2016 (see Figure 9). No adverse effects were detected in the AACS telemetry from the first periapsis crossing either, or any of the later periapsis crossing events, that could indicate that dust impact had occurred to the Cassini spacecraft. No instantaneous spikes in attitude control error or system momentum were observed.

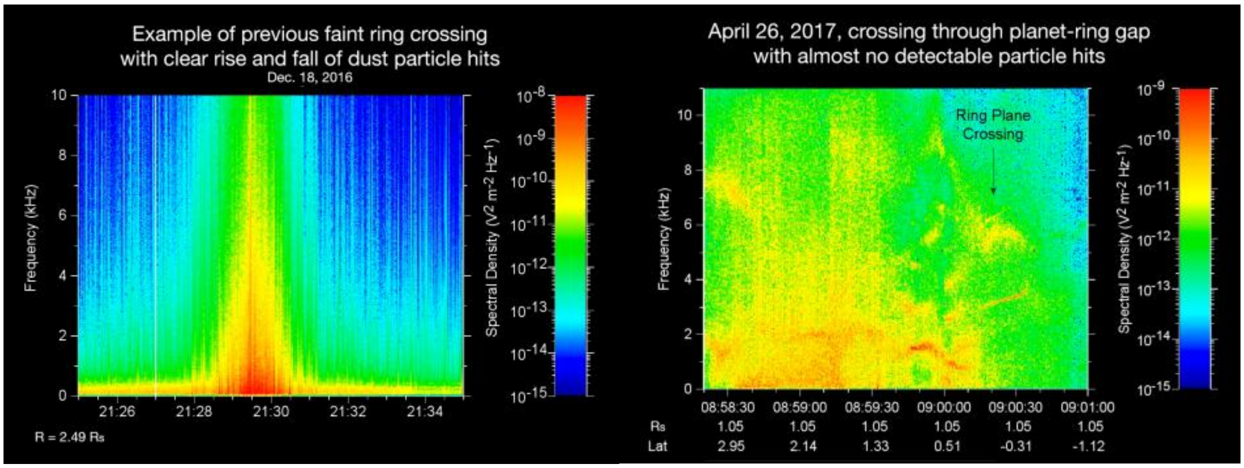

Figure 9. Dust frequency results from the Radio and Plasma Wave Spectrometer. The left plot shows the dust frequency from a F-ring crossing comparing to the right plot showing dust frequency after the first proximal orbit. (Courtesy of Cassini RPWS team at University of Iowa and Jet Propulsion Laboratory)

The strategy of pointing the HGA to dust RAM to protect the sensitive instruments on the spacecraft bus had a trade-off – Cassini's two sun sensor assemblies were mounted inside the HGA dish. While the SSAs were not used in nominal attitude estimation, they were vital instruments to fault protection recovery should anomalies occur. To check its health along with the prime SSA, the backup SSA was powered on prior to any critical ring plane crossing event. During the first downlink pass after a dust hazard, when Cassini had communications with the ground, the spacecraft was commanded to rotate about the Z-axis (rolling about the Earth-line). This would put all four quadrants of each sun sensor into the sun-line during the slew, so the readings (sun location and intensity) from both sun sensor heads of each SSAs could be evaluated to detect any debris-caused damage in a timely fashion. The first proximal orbit periapsis crossing was handled the same way and a SSA checkout was conducted. The results confirmed that both SSA units were healthy and tracking the sun as expected. In Figure 10, the predicted sun-line as seen in the sun sensor assembly is plotted in blue with sun sensor head 1 data plotted against sun sensor head 2. The results for SSA assembly A is plotted in red on top of the expected predicts, while the SSA assembly B is plotted in green on top of the expected predicts. The results from Figure 10 showed that both SSA assemblies, each with two sun sensor heads, survived the first proximal ring plane crossing without any noticeable damage. The four subsequent proximal orbit periapsis crossings with the HGA-to-RAM attitude commanded also had SSA checkout activities planned post the ring plane crossings. Telemetry

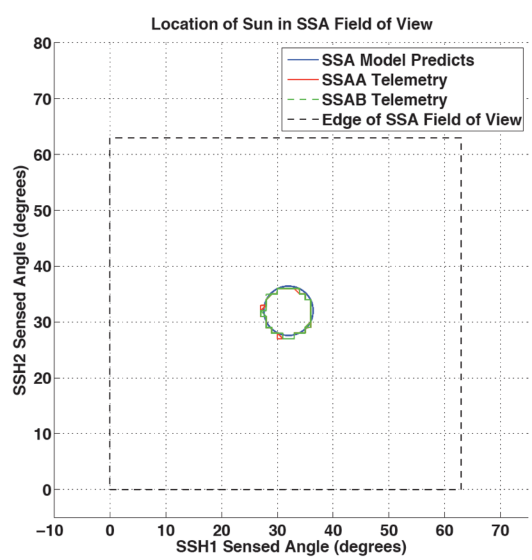

Figure 10. Cassini Sun Sensor Checkout telemetry after the first proximal orbit periapsis crossing.

showed healthy SSAs through all critical ring plane crossing activities. It is also important to note that contingency SSA checkout activities were also designed should the contingency HGA-to-RAM attitudes be necessary.

Although a benign dust environment was good news to the Cassini engineering team, it posed a problem to the Cassini science team. Was Cassini in a region that had just *too little* dust to obtain proper sampling of the dust environment? While the majority of the periapsis crossing orbits were designed with the attitude pointing the Cosmic Dust Analyzer (CDA) towards the dust stream direction, the orbits where Cassini was to fly closest to the D-ring were designed with the risk-mitigation attitude of HGA-to-RAM to shield the spacecraft instruments from the dust direction. What if the dust model was over predicting the dust hazard for those orbits too? By the fourth periapsis crossing event, the Cassini operations team started assessing the likelihood of redesigning one of the D-ring orbits to allow for better sampling of the dust. Throughout Cassini's mission at Saturn, sequence development usually started as early as 6 months in advance prior to execution. During the 6 months planning period, multiple simulations and tests were performed to ensure that the commands were properly implemented with no risks to the spacecraft health. To redesign the spacecraft pointing so close to real-time execution (about a month prior) was a highly unusual practice. As previously mentioned, the Cassini operations team had pre-designed and pre-tested the contingency sequences to turn the spacecraft to point HGA-to-RAM direction early in the development phase in case dusts were higher than predicted. This time, however, the science teams were asking for the complete opposite of that strategy – to undo a pre-designed risk mitigation attitude already on board the spacecraft. This was also a highly unusual practice. Nevertheless, this extremely rare opportunity to directly sample the dust particles of the D-ring was worth the last minute redesign. After AACS analysis showed that the science observations prior to and following the ring plane crossing would not be interrupted, and that no additional risks including interferences to star field of the SRU and science instrument heating were introduced, the operations team redesigned and uplinked a 40 degree turn to override the background sequence HGA-to-RAM attitude in favor of the science friendly attitude for the 11th proximal periapsis crossing (Figure 11). The better sampling of the dust particles resulted from this pointing redesign turned out to be a success to the science community.

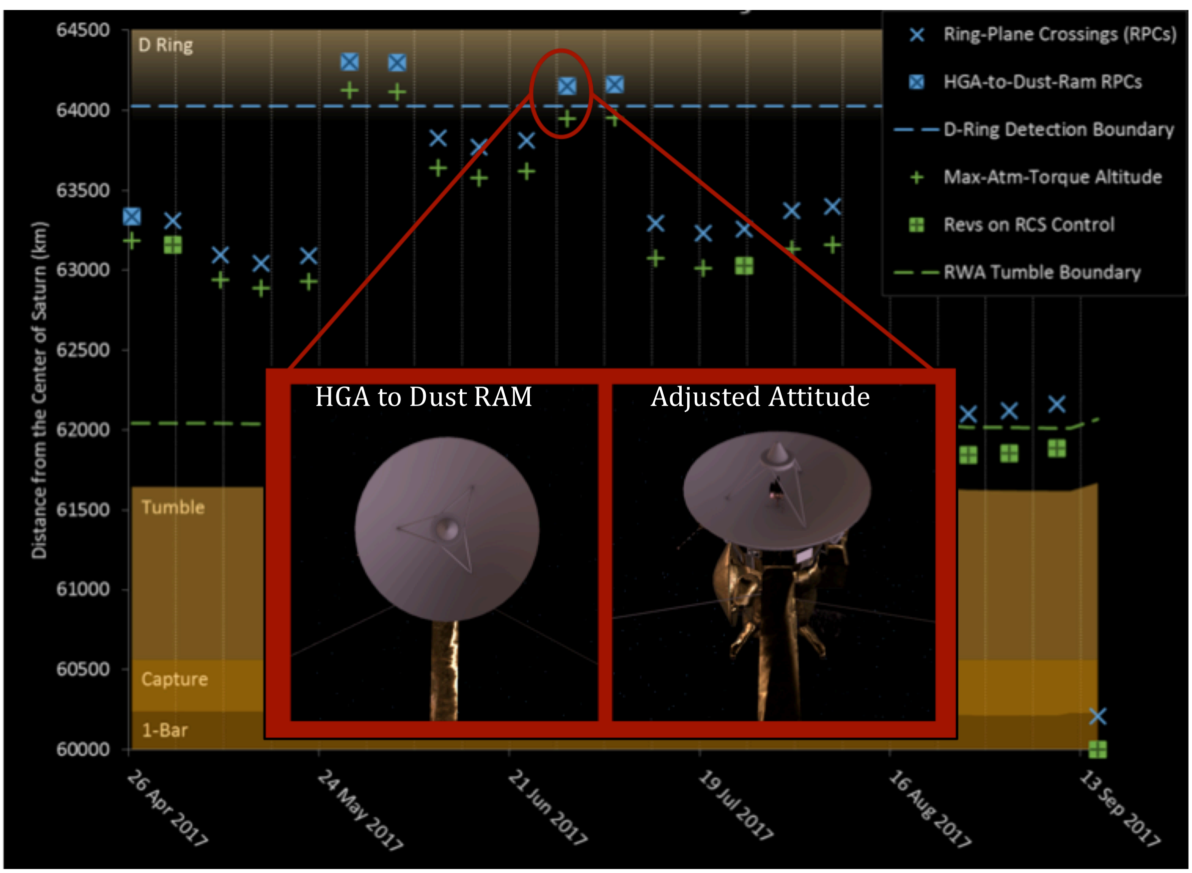

Figure 11. Last minute attitude control redesign was implemented during Cassini's proximal orbit operations due to lack of dust detected after the first periapsis crossing. From this image, the reader is in the Cassini velocity direction where dust would have been encountered from the spacecraft point of view.

IV. Spacecraft Controllability During Proximal Flybys

RWA and Gravity Gradient Torque

Similar to the dust hazard analysis, early studies were conducted to assess the control authority of the Cassini spacecraft flying through the 22 proximal orbits closer to Saturn than ever before. A Saturn atmospheric density model was developed using data from stellar and solar occultation observations gathered by the Ultraviolet Imaging Spectrograph (UVIS) instrument on Cassini. In 2013, this density model was incorporated into the Cassini ground simulation tool to help engineers assess the RCS and RWA control authority at desired spacecraft attitudes for the various altitude flybys. The ground simulation tool also helped predict the hydrazine cost of RCS flybys, the would-be ΔV imparted onto the spacecraft, and potential fault protection scenarios. In addition to Saturn's atmospheric drag torque, additional external disturbances were also modeled: Saturn's gravity gradient torque, magnetic disturbance torque, solar radiation and RTG radiation torque, and target motion compensation torque. The Cassini spacecraft's center-of-pressure and moment arm torque models followed the same approach as numerous low-altitude Titan flybys Cassini had performed. Uncertainties were also included to provide appropriate bounding conditions to address controllability margins.

For the first 17 proximal orbits, the lowest altitude predicted was roughly 1,950 km above Saturn's cloud tops. The peak atmospheric torque using the density model was estimated to be roughly 0.14 Nm. The other sources of torque, while small in comparison, were also accounted for. Gravity gradient torque was estimated to be under 7.0e-4 Nm; solar radiation and RTG radiation torques were estimated to be roughly 2.0e-6 Nm, and the torque induced by Cassini's residual magnetic field interacting with Saturn's magnetic field was estimated to be around 1.0e-4 Nm. The "target motion compensation" torque, a torque required for the spacecraft to track moving objects, was estimated to be 1.3e-3 Nm. For RWA control, the per wheel torque needed to support these combined environmental torques was derived to be 0.082 Nm each. Adding torque needed for attitude control (~0.004 Nm), RWA drag torque (~0.02 Nm), and gyroscopic torque (~0.012 Nm), the total torque needed per wheel for a worst-case flyby of the first 17 proximal orbits would be roughly 0.118 Nm. This was still within the RWA available motor torque of 0.165 Nm, and therefore, the RWAs were able to support the first 17 proximal orbit flybys, as long as no additional spacecraft slews were commanded during the periapsis crossings. Some observations, however, like those done by Cassini's Magnetometer instrument, required the spacecraft to be rolling during periapsis crossings in order to obtain proper measurements. For these observations, additional slew torque required for the system could be as much as 0.045 Nm; therefore, RCS control was used for these types of observations, which also allowed faster slew rates to be utilized.

As expected, the RWAs had no problem controlling the spacecraft during these early periapsis crossings, reaching as low as 1,950 km above Saturn's cloud tops. One of the torques assessed, Saturn's gravity gradient torque, showed interesting signatures in the RWA telemetry. Gravity gradient torque occurs on a spacecraft due to variation of the planet's gravitational force applied over the spacecraft, creating a torque around the spacecraft's center of mass. Note that the gravity distribution on the spacecraft is dependent on the spacecraft attitude in addition to the mass configuration, so not all flybys experience the same gravity gradient torques. When a spacecraft on RWA control experiences a gravity gradient torque disturbance, this torque causes a change in angular momentum that can be seen in the reaction wheel speeds, even though the spacecraft remains at a fixed attitude.[6] Cassini had encountered gravity gradient torques many times over the course of the mission with low altitude flybys past Dione, Rhea, and Enceladus. In fact, the disturbances imparted by these Saturnian moons onto the Cassini spacecraft helped improve the modeling of gravity gradient torques of these moons. Although this was the first time any spacecraft had ever flown so close to Saturn, the signatures of gravity gradient torque imparted on Cassini had similar characteristics to the gravity gradient torque observed during the low altitude flybys of the moons. It could be seen that during the hours leading up to the closest approach of Saturn over certain periapsis crossing events, Cassini's RWA spin rates showed accumulated momentum from the gravity gradient torque. During the hours after closest approach, some of the accumulated momentum dissipated, again due to gravity gradient torque. Figure 12 shows the RWA wheel speeds as designed for the periapsis crossing on June 10th, 2017 versus wheel speeds observed in the telemetry. A change in wheel speeds of as much as 50 revolutions per minute (rpm) was seen. Similar signatures were also observed in a few other periapsis crossing orbits, showing consistent effects of the Saturn gravity gradient torque exerted on the Cassini spacecraft.

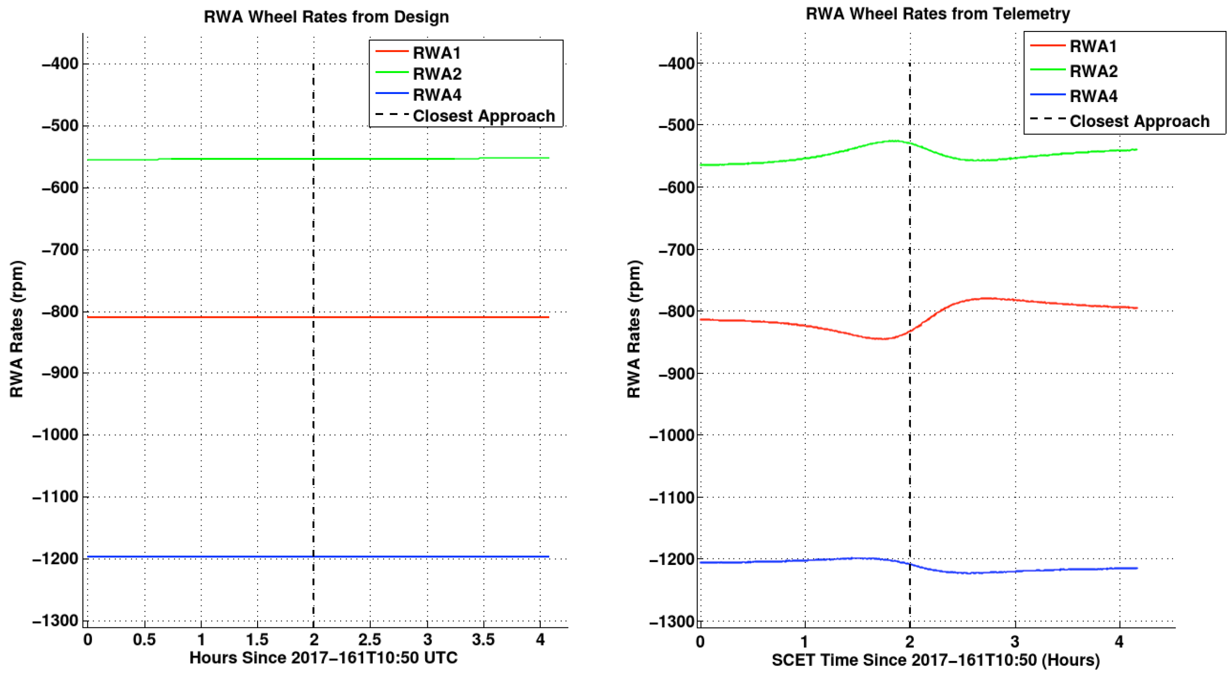

Figure 12. RWA wheel speeds as designed versus observed from telemetry. Gravity gradient torque effects of Saturn (right plot) were evident in RWA wheel speeds.

RCS and Low Altitude Flybys of Saturn Upper Atmosphere

The last five periapsis crossing events before the final plunge put Cassini in a much lower altitude than the previous orbits, around 1,600 km above Saturn's 1-bar atmosphere region. The aerodynamic density model estimated this region to impart torques as much as 0.9 Nm, which was beyond the control authority available on RWA control. Therefore, RCS thrusters had to be used in the final 5 orbits. Although launched with 0.9 N thrust available per thruster, the thrust force had degraded to 0.57 N per thruster after 20 years of usage due to hydrazine tank pressure decay as propellant was depleted. Assuming an additional 7% degradation for margin, the per-axis control authority of the RCS thrusters ranged from 1.0 Nm to 1.6 Nm, still capable of keeping control authority during low altitude Saturn flybys even accounting for the other environmental torques previously discussed. To avoid induced gyroscopic torque, however, the RWAs were powered off for each of the RCS controlled periapsis orbits.

With the torque models implemented in the ground simulation software, these low-altitude periapsis crossing events were tested by the attitude control team. RCS thruster peak duty cycles, the percentage of thruster firings the RCS system had to use to keep control authority, were predicted to be 10 to 20%. In flight, the actual peak duty cycles ranged from 30 to 45%. This meant that the Saturn atmosphere was about 3 times denser than the predicted model, since the RCS thrusters had to fire 3 times more than expected! Figure 13 shows the RCS peak duty cycles for each of the final 5 orbits in body Z-axis and body Y-axis in prediction versus telemetry. Fortunately, the duty cycles showed that the RCS thrusters still had sufficient margin before reaching 100% duty cycle, the point at which the thrusters would be saturated and the spacecraft would tumble. Instead, at 30 to 45% duty cycle, Cassini remained stable while the science instruments obtained stronger in-situ sampling of the Saturn atmosphere than planned. The AACS RCS telemetry and duty thruster trending from these last 5 orbits can now be used to improve the Saturn atmospheric model, much like the Titan and Enceladus density reconstruction models that AACS was able to produce. The discussion on how Saturn atmospheric drag torque and in turn the Saturn density are derived using RCS commanded torque from these last 5 low-altitude flybys is presented in a different paper.[7]

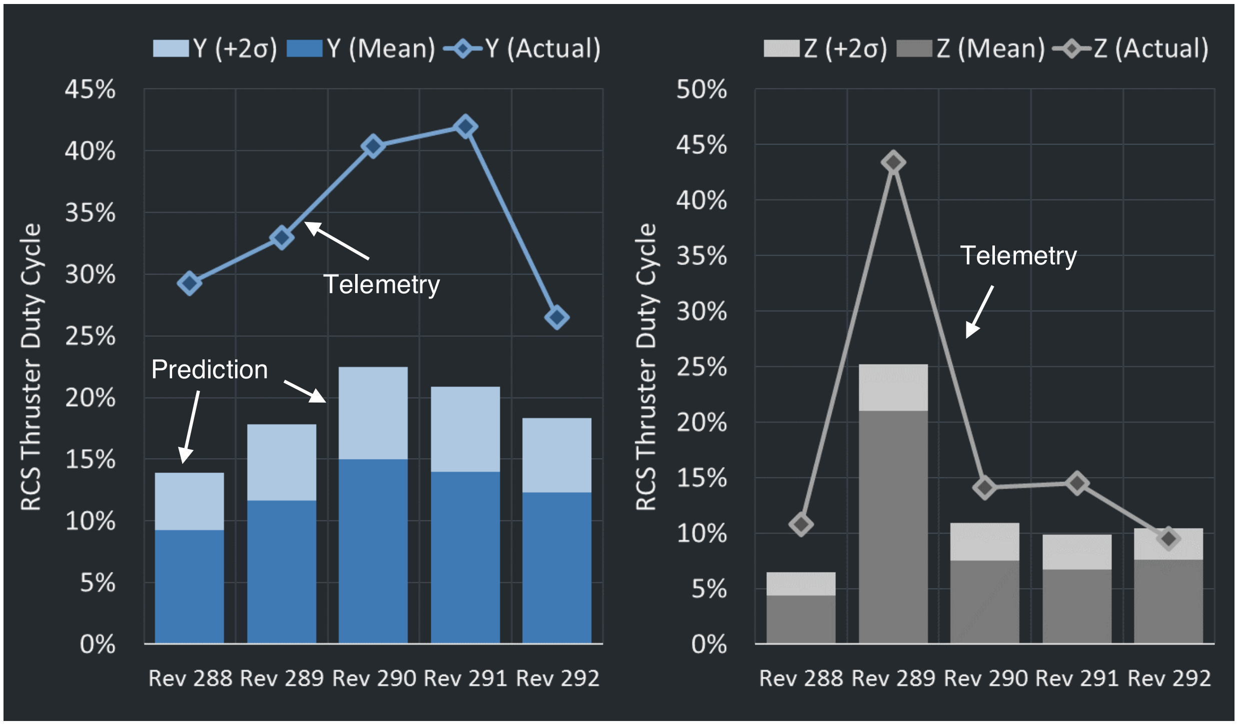

Figure 13. RCS thruster duty cycles for the final 5 periapsis crossing orbits prior to the final plunge. Y thruster performances are shown on the left and Z thruster performances on the right. (Courtesy of Erick Sturm of Jet Propulsion Laboratory)

Contingency Maneuvers

To ensure that Cassini remained healthy and stable until the very end, contingency maneuvers were planned to account for under or over estimation of the Saturn atmospheric density model. The first of the five Saturn-skimming periapsides occurred on August 14, 2017. Closest approach to Saturn was about 1,706 km. The later four periapsides, each one week apart, dipped even lower into Saturn's atmosphere (by as much as 80 km). If the peak thruster duty-cycle on August 14th was above 70%, risk of tumbling on the four lower periapsis crossings soon to follow would be high. To mitigate this risk, a contingency main-engine ΔV maneuver could have been executed on August 17th to raise the subsequent periapsis altitudes for the remaining Saturn flybys so that proper margins from tumbling risks were included. This was called a contingency "pop-up" maneuver. On the other hand, if the peak duty cycle was below 10%, a "pop-down" maneuver could have been executed to allow for better in-situ sampling of the Saturn atmosphere. In the end, even though the Saturn atmosphere observed turned out to be higher than the model predicted, Cassini was not at risk of tumbling but still offered tremendous first ever in-situ data of the Saturn atmosphere. Hence, the contingency "pop-up" or "pop-down" maneuvers were not needed.

V. Radiation Hazards

The Magnetosphere Imaging Instrument (MIMI) on board the Cassini spacecraft was a neutral and charged particle detection system designed to perform both imaging and in-situ measurements on Saturn's magnetosphere. Even prior to SOI, MIMI was able to begin characterizing Saturn's main radiation belt during approach to Saturn. Throughout the mission at Saturn, MIMI analyzed and interpreted observations of energetic neutral atoms originating from the gap between the rings and Saturn. It was found that the proton intensity within this gap would be drastically lower (less than 10%) than further outside of Saturn's rings at the Janus/Epimetheus orbits, which cross the strongest radiation area of the main radiation belt.

The Cassini spacecraft had many experiences dealing with radiation, starting as early as the Earth flyby gravity assist in 1999 at a close-approach altitude of 1,175 km. Throughout Cassini's mission, the Cassini spacecraft continued to experience radiation effects, and it was found that the high energy proton deposited in the front end of the IRU HRG buffer led to spikes in the gyro angle pulses, effects called Single Event Transients (SET). The MIMI radiation model was implemented in the ground simulation software, which allowed Cassini engineers to inject radiation induced SET to the gyro data to validate the threshold and persistence limits in the fault protection monitor to ensure robustness against the SETs. This fault protection monitor was a parity check between the four HRG pulse rates. Normally, the sum parity should be close to zero. This monitor had since become a useful error monitor to track radiation effects on the IRU. Telemetry in Figure 14 shows the SET events experienced by Cassini's IRU from late 2015 through the proximal mission. It can be noted that the proximal mission indeed experienced smaller rate spikes in comparison to SET events over orbits closer to the outer rings of Saturn.

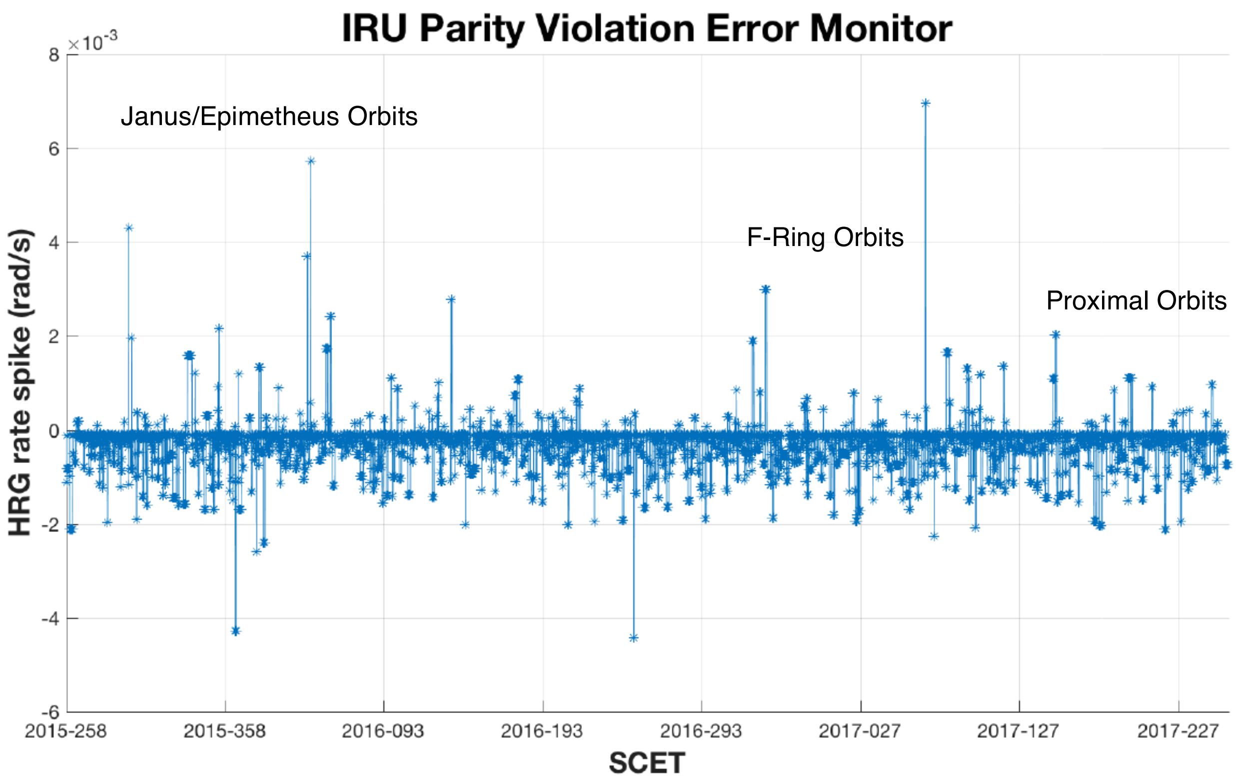

Figure 14. IRU HRG rate spikes shown in the parity violation error monitor from late 2015 through end of mission.

The threshold on the IRU parity violation monitor was a dynamic limit that bounded the "expected" magnitude of rate spikes. It was a function of the four HRG orientations relative to one another, the pulse rates, and other IRU hardware parameters, including gyro quantization, rate noise, scale factor errors, and misalignments.[3] The fault protection persistence limit, the duration where a parity violation remained over the threshold limit, was tuned earlier in the mission. The gyro manufacture simulation data showed that all traces of SET-induced transients disappeared within 0.75 seconds. As such, the IRU parity violation fault protection persistence limit was tuned to be twice that value, at 1.5 seconds, in order to provide margin against false alarms due to these radiation-induced rate spikes.[3] In flight, these SET events, while occurring often, had a short persistence that was below the fault protection persistence limit. The gyro data from these SET events were therefore edited and filtered out by the flight software and digital filters before being fed to the RCS/RWA controller. As a result, impacts of the SETs on the attitude estimation and control functions were proven to be negligible. For the proximal orbits, ground simulation tools validated the persistence limit and concluded that an update was not needed. The IRU performed as expected through the proximal orbit periapsis crossing events.

Cassini's Solid State Recorders were also susceptible to environmental effects. Single Bit Errors (SBEs) and Double Bit Errors (DBEs) often occurred in the presence of radiation. The flight software routinely detected and corrected for SBEs and DBEs so the SSRs continued to function nominally. Interestingly, the detection of SBEs and DBEs had turned the SSRs into uncalibrated and unofficial radiation detectors. The correlation between SSR SBEs and the high radiation environment was even stronger than observed in the IRU. Figure 15 shows the effects of

Saturn radiation on the SSRs. The results were consistent with MIMI's radiation model over the region between Saturn and the rings in comparison to the radiation effects over the outer rings of Saturn.

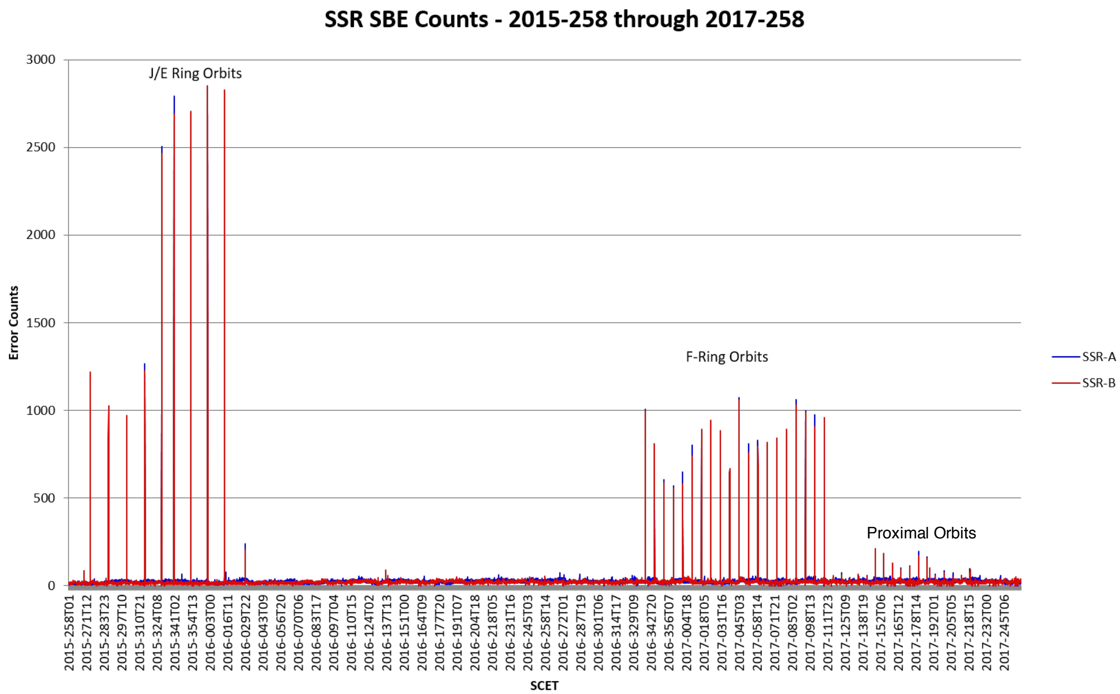

Figure 15. SSR single bit error counts from late 2015 through the proximal mission.

VI. Saturn and Ring Interferences to the Star Tracker

An extended bright body such as Saturn, its rings, and its satellites, if in or near the star tracker's field-of-view, could degrade the SRU's ability to track stars. To mitigate this problem, ground engineers routinely commanded the star identification to be "suspended" over each predicted period of bright body interference. During these periods, the flight software propagated inertial attitude knowledge using the IRU data alone. However, IRU scale factor errors and misalignments would degrade the IRU-only estimates over time. Therefore, flight rules were established to limit the maximum allowed "SID suspend" duration to 5 hours. Additionally, all SID suspend events had to begin and end with the spacecraft in a quiescent state, with the total spacecraft body rate below 0.5 mrad/s prior and 0.4 mrad/s post the suspend duration.[4]

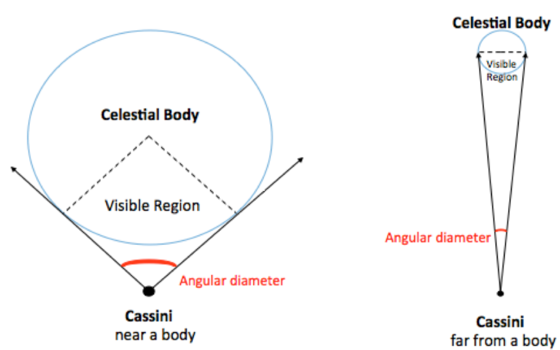

Figure 16. Angular diameter of bright bodies from Cassini's perspective.[4]

During Cassini's mission at Saturn, the planet and its rings dominated the sky from Cassini's perspective and accounted for most of the SID suspend cases. As Cassini traveled through its orbits around Saturn, Saturn could appear to be as small as 2 degrees in angular diameter at apoapsis and could grow to over 150 degrees at periapsis, filling almost half the sky from Cassini's perspective.[4] The angular diameter is the angle of the cone that circumscribed the bright body object from Cassini's field of view (Figure 16). During the proximal orbit mission, Cassini flew closer to Saturn than ever before. Saturn was predicted to span up to 160 degrees in the angular diameter while the rings extended the bright body region by another 90 degrees. Figure 17 shows the predicted angular diameter of Saturn and its rings when the visible part of the rings extended the Saturn bright body region during a proximal periapsis period. The combined angular diameter reached over 250 degrees. In other words, the bright bodies blocked more than half of the sky from Cassini's perspective. With SRU's 30-degree stray light field-of-view factored in, only a small star field of around 30 degrees by 30 degrees was visible, with this field changing abruptly from above the ring plane to below the ring plane. This added additional complexity to the SRU's ability to track stars. Fortunately, with Cassini traveling at about 34 km/s near the periapsis crossings, all 22 proximal orbits had attitude designs that limited the Saturn and rings bright body interferences to under 5 hours. Therefore, these interferences were proven to not be an impact to typical operations.

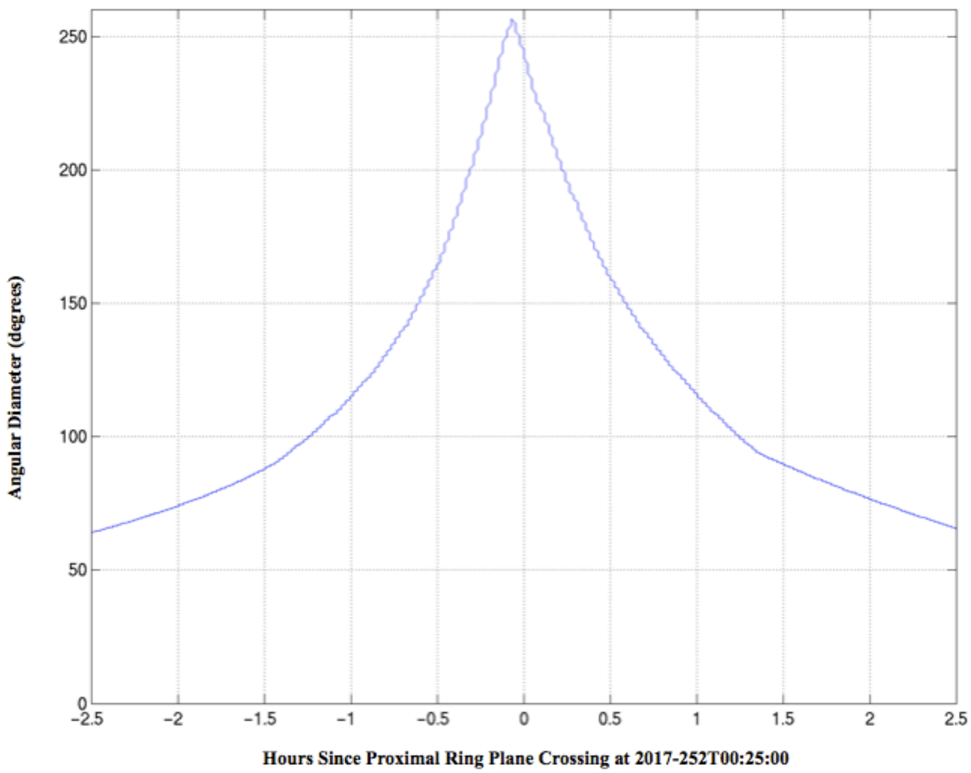

Figure 17. Angular diameter of the combined Saturn and rings bright body during closet approach of the last proximal flyby prior to plunge as seen by the Cassini spacecraft.[4]

Special considerations had to be made, however, on the selection of "safe mode attitudes", which were Cassini's default orientations should an anomaly occur. If Cassini were to enter safe mode, the safe mode attitude needed to ensure a commandable spacecraft, a benign thermal environment, a clear star field, and the ability to play back data to help ground controllers assess the anomaly.[8] During a safe mode event, all nominal sequences would have been stopped, and an entire proximal flyby may have occurred at the safing attitude without any suspension of SID. To ensure commandability, safe mode attitudes had to point the HGA to Earth. The pointing of the SRU boresight, which was perpendicular to the HGA boresight, needed to be managed by the attitude control engineers to point to a clear field-of-view to limit complications to the anomaly resolution and further risks to the spacecraft health. During the proximal orbit mission, there was no single attitude that provided a clear star field throughout closest approach. As previously shown, most of the field of view of Cassini during proximal orbit periapsis crossings was obstructed by Saturn and its rings. Furthermore, a clear field of view before the periapsis crossing quickly became obstructed after Cassini passed through the rings. The best alternative for the safe mode attitude was to utilize an attitude that minimized the time of SRU bright body interference as much as possible. After analysis conducted by the attitude control engineers, safe mode attitudes were selected where the bright body interferences lasted no more than 60-90 minutes. Two different safe mode attitudes were chosen: the first was a -105 degree Z-axis offset from the baseline safe mode attitude that spanned the first 11 proximal orbits, and the second was a +65 degree offset from the baseline safe mode attitude that spanned the last 11 proximal orbits. Ground simulation validated the safe mode attitudes and demonstrated that IRU propagation errors within a 60-90 minutes interference window were benign. The two safe mode attitudes were stored into the flight software memory. Fortunately, the Cassini spacecraft did not experience a safe mode event in the last 22 orbits of the mission.

VII. Trajectory Deviations and Live Vector Updates

In the 13 years at Saturn, Cassini's orbit path was designed to closely follow the planned reference trajectory. When deviations occur, ΔV maneuvers were executed to return Cassini to the reference trajectory. These deviations were caused by uncertainties in Saturn gravity field, positions of the moons, atmospheric drag during low-altitude Titan flybys, and small ΔV imparted on the spacecraft during momentum dump biases.[9] At times, maneuvers would be cancelled which allowed the Cassini trajectory to deviate even more from the reference trajectory until the next maneuver. These deviations sometimes affected the pointing accuracy of the pre-designed background sequences, and therefore updates to the pointing had to be made to keep objects in the field-of-view of the science instruments. Drag uncertainty during the final five Saturn atmosphere-skimming periapsides played a crucial role in imparting trajectory deviations. Also, there were no planned ΔV maneuvers after July 15th, 2017. As a result, deviations from the reference trajectory were the largest Cassini had experienced in flight. Near the end of the mission, the trajectory had shifted 8 minutes and 19 seconds earlier in comparison to the background sequence design. This shift led to pointing errors up to 15 degrees that needed to be corrected.

Cassini's pointing commands were designed using vectors.[9] Targeting vectors were represented by vectors that expressed the position of the celestial objects relative to the spacecraft. Some of these vectors varied in time as celestial objects moved in space, and some were inertially fixed vectors. Body vectors represented the boresights of spacecraft body-fixed instruments. Commands were constructed by calling for a primary and a secondary body vectors to be aligned with the target vectors, with the third body axis naturally completing the coordinate system. Over the course of the mission, an average of 17 pointing commands were issued per day, totaling over 82,000 targeting commands issued by the end of the mission. To perform a live vector update to account for the trajectory deviations, new targeting vectors were constructed using the latest ephemeris file, which provided the latest information on the position of the spacecraft. These new targeting vectors were then placed at a time that superseded the old vectors from the background sequence before the turn took place. Essentially, "overlay" sequences were built to replace the old targeting vectors already loaded on board the spacecraft with the new ones that corrected for the trajectory discrepancies. One particular vector, the Saturn-to-Cassini vector, was always in use, or "active", so special care was required to ensure that the vector update would not create an instantaneous discontinuity in the pointing, which could lead to fault protection responses. To accomplish this, the spacecraft had to first be commanded to point at a fixed inertial direction without using the Saturn-to-Cassini vector while the updates were commanded. Once the vector was updated, the spacecraft could then be commanded back to point with the new vector and continue with the background sequence commands. Since orbit determination was a time-critical navigation process, new ephemeris files were released near the time they were needed. Often times, ground operators had less than a week to design new vectors, test them against the existing background sequence, and uplink the overlay for execution.

The process of live vector updates was practiced routinely throughout Cassini's mission at Saturn. However, since maneuvers were also routinely executed to keep Cassini close to the reference trajectory, each live vector update usually contained only a few vectors at a time to correct the pointing of the most sensitive observations. For the last 7 days of the proximal orbits mission, about 90 vectors were updated, which was the largest update performed in flight. In addition to the vector updates, a number of commands surrounding the last few periapsis crossings of Saturn also had to be shifted in time to account for the timing deviations. The process of shifting the commands in time was also a routine task, but in most cases the deviations were less than a minute or two. Even though existing operational procedures accommodated the trajectory deviations during the proximal orbits mission, the Cassini operations team was challenged with larger deviations and a much greater update volume in the short period of time. Fortunately, the robust ground tools and the established procedures helped the attitude control engineers overcome the challenge.

VIII. Fault Protection Anomalies and Contingency Recovery Plans

The Cassini operations team did an extensive amount of work over the years prior to the proximal orbits mission to assess the possible risks and mitigation plans for this phase of the mission. Many were discussed in the previous sections of this paper. However, to ensure that all possible scenarios were accounted for, even the ones that were not thought of, the final fail-safe scenario to consider was safe-mode recovery. If for whatever reason the Cassini spacecraft suffered an unexpected anomaly and entered into safe-mode, the on-board sequence would be abandoned by the flight software and the spacecraft would autonomously turn to the safing attitude to await ground response. Although the ballistic trajectory Cassini was on guaranteed that the spacecraft would decommission by flying into Saturn's atmosphere on September 15, 2017, in safe mode Cassini would have ended the mission without the ability to conduct the last valuable science observations, and the chance to obtain the first ever sampling of the Saturn atmosphere would be lost. Therefore, it was crucial for the Cassini operations team to be able to quickly return the spacecraft back to science operations prior to the final plunge, should a safe mode event occur.

Typically, if a safe-mode occurred, procedures were in place to help the operators diagnose the anomaly prior to recovering the spacecraft, since recovery strategies may differ for various different anomalies. Although the desire would still be to recover the spacecraft as quickly as possible to return to science observations, careful planning had to be made to not agitate the fault scenario or complicate the recovery process. Therefore, there was no existing recovery timeline and recovery command sequences readily available. Unfortunately for the proximal orbits mission, time was of the essence. To ensure that the Cassini spacecraft could be recovered even if a safe mode occurred within 14 hours of the final plunge, pre-designed contingency recovery sequences were built and put "on the shelf" to allow for an expedited turn-around time. This meant that as soon as a safe-mode was detected, the contingency recovery "mini-sequence" would be available to command the spacecraft back to Earth-point as soon as possible to allow communications, power back up the crucial instruments necessary for the final science observations, and turn to the science attitude in preparation for the final plunge. For attitude control, special commands were ready to establish the science attitude, as well as commands to suspend star identification. For AACS reconstruction of the Saturn atmospheric density, a special downlink "telemetry schedule" to increase frequency of certain RCS thruster telemetry also needed to be included in the contingency mini-sequence. Masking of the excessive thruster commanding was also required to ensure that no additional fault protection would be triggered during the final plunge when the thrusters began to fight the atmosphere. These commands were already loaded on board from the background sequence, but would have needed to be reissued had a safing event occurred.

This contingency recovery mini-sequence was developed and tested. Ground simulation of various safe mode scenarios were conducted and the mini-sequence was proven to be able to recover the spacecraft even at 14 hours prior to the final plunge in various different fault scenarios. Fortunately, a spacecraft safing event did not occur in flight. However, if it had, the Cassini operations team was confident that the spacecraft could have been recovered quickly and the last science observations planned for Cassini during the final plunge could be salvaged.

IX. The Final Plunge

On September 11th, 2017 at 12:04 pm PDT, a last distant flyby of Titan nudged Cassini to its last orbit towards Saturn. On September 14th, 2017 at around 12:58 pm, Cassini took the last images of the location where the plunge on Saturn was to occur. At 3:30 pm, the RWAs were powered off for the last time, so that the remainder of the mission was conducted on RCS control. At 1:30 am PDT on September 15th, 2017, the Cassini spacecraft reconfigured itself to the final science attitude and for real-time science retransmission. In the hours leading up to the final plunge, Cassini was on RCS control with an attitude controller error, or deadband limit, of [0.5, 0.5, 2] mrad for the spacecraft body X, Y and Z-axis, respectively. The RCS control algorithm had internal logic that attempted to preserve hydrazine by changing the firing rate of the RCS thrusters depending on the disturbances. At 4:53:45 am, the RCS thrusters transitioned to "high-rate" thruster control, which indicated that the spacecraft had entered Saturn's atmosphere and that the thrusters required a higher firing rate to fight the Saturn atmospheric density torque. Very soon after that, the attitude control errors were observed to be "riding the deadband". This meant that the RCS thrusters were firing very close to 100% duty cycle in attempt to keep the spacecraft attitude control errors within the deadband limits. The atmospheric torque eventually became too powerful for the RCS thrusters to overcome, and the spacecraft began to roll about the Z-axis. Soon after, the Z-axis where the HGA was pointed towards the Earth line also began to turn away (see Figure 18). At 4:55:19 am, the final telemetry from Cassini was received and the start of the spacecraft tumbling was observed. The downlink antennas at the Deep Space Network were able to hold on to the carrier signal a bit longer. The X-band carrier lock was lost at 4:55:39 am, and then finally, the last signal from the S-Band carrier was lost at 4:55:43 am.

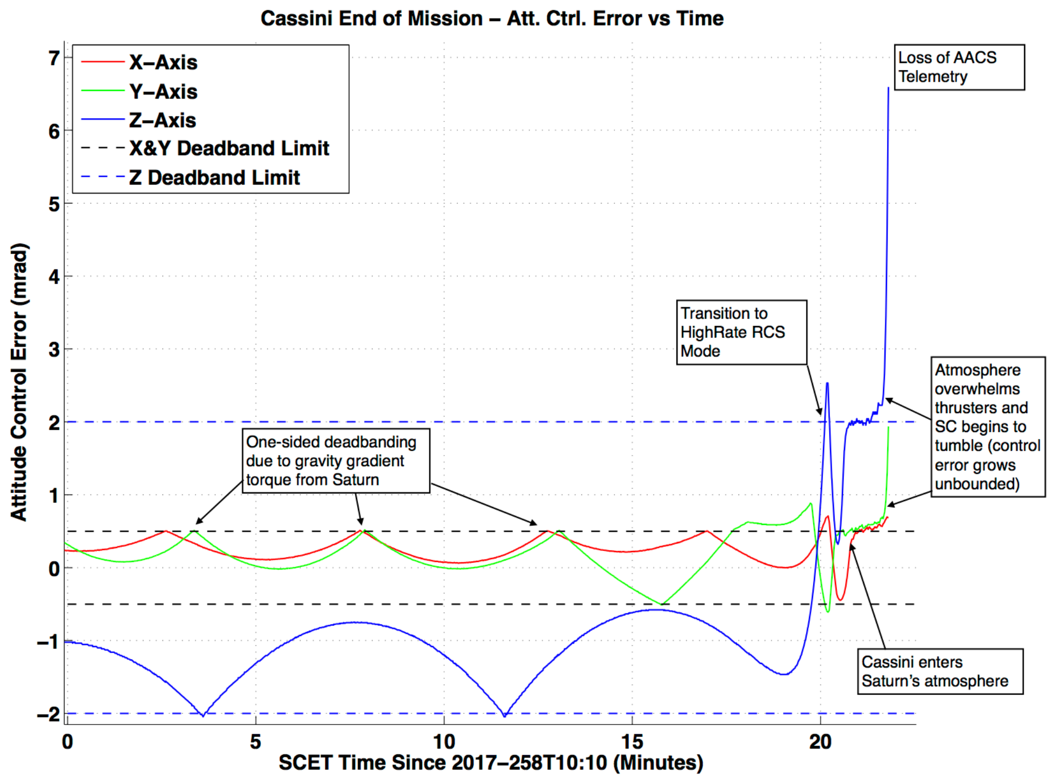

Figure 18. The final telemetry of Cassini's attitude control error showing the RCS thrusters attempted to fight the Saturn atmospheric torque as the spacecraft entered Saturn's atmosphere.

Figure 19 shows the RCS thruster duty cycles averaged per 8-second samples for the last 2 minutes prior to spacecraft tumbling. The transition to high rate RCS mode can be observed around 100 seconds prior to loss of signal (LOS). About a minute prior to LOS, the thruster duty cycles were seen rapidly increasing, as the spacecraft fought the keep the spacecraft stable. Figure 20 shows the last 20 seconds of the peak duty cycles averaged per second for the Z4 thruster and the Y2 and Y4 thruster pair. Telemetry showed that the Y2 and Y4 thruster pair reached 100% duty cycle first, at around LOS -11 seconds. This was consistent with the attitude control error telemetry shown in Figure 18, where Z-axis attitude control error moved out of the deadband limit first, indicating that the spacecraft was starting to roll out of control around the HGA-to-Earth line. At LOS -9 seconds, the Z4 thruster reached 100% duty cycle, at which point the spacecraft began turning away from the Earth line. Table 1 below shows the per-second break down for the last 20 seconds of the RCS duty cycle telemetry.

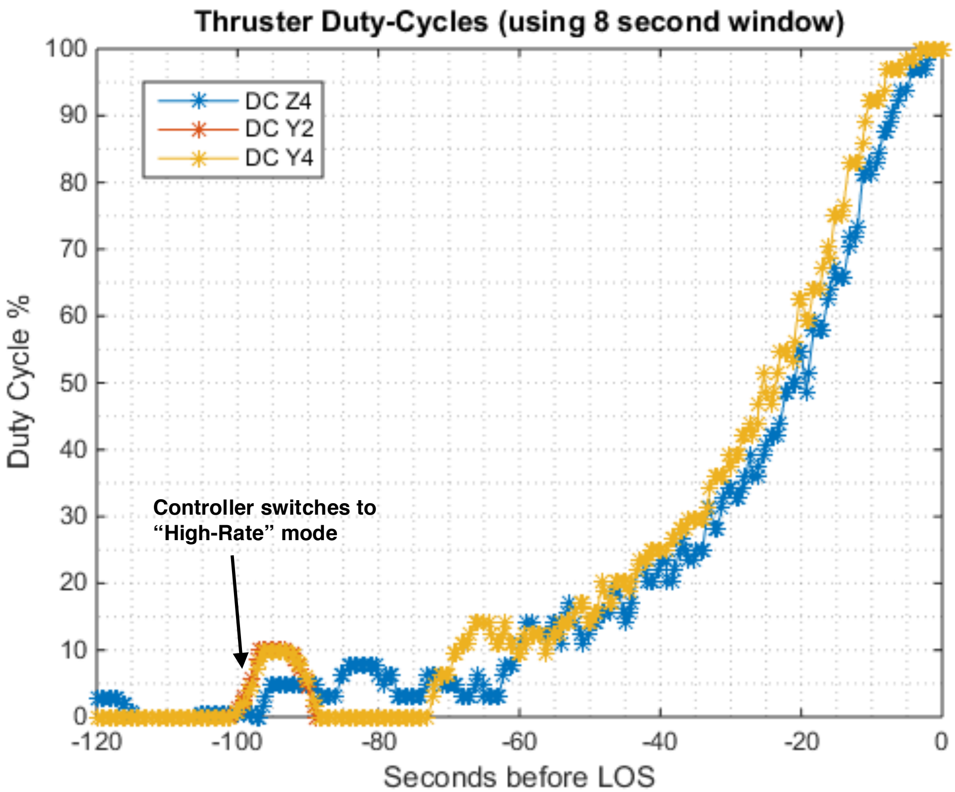

Figure 19. Thruster duty cycles for the last 2 minutes of flight of the Z4 thruster and the Y2 and Y4 thruster pair.

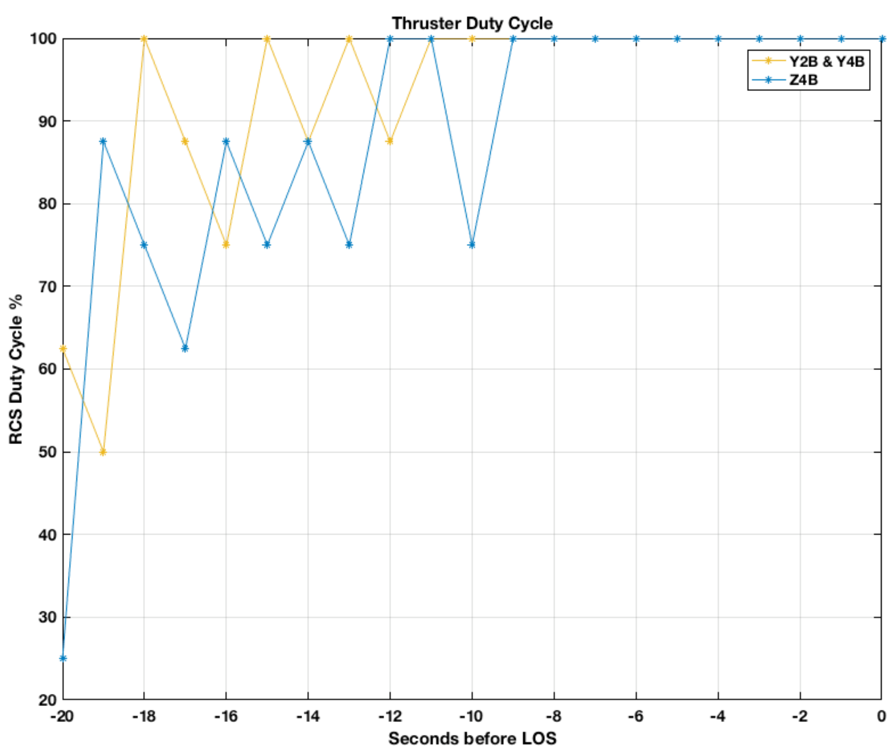

Figure 20. Thruster duty cycles for the last 20 seconds of flight of the Z4 thruster and the Y2 and Y4 thruster pair. It was observed that the Y2 and Y4 thruster pair reached 100% duty cycle first.

Table 1. Thruster duty cycle for the last 20 seconds of flight.

Time to LOS (sec)	Predicted Altitude (km)	Y2B/Y4B Pair Duty Cycle (%)	Z4B Duty Cycle (%)
-20	1540	62.5	25
-19	1533	50	87.5
-18	1526	100	75
-17	1520	87.5	62.5
-16	1513	75	87.5
-15	1506	100	75
-14	1500	87.5	87.5
-13	1493	100	75
-12	1486	87.5	100
-11	1480	100	100
-10	1473	100	75
-9	1467	100	100
-8	1460	100	100
-7	1453	100	100
-6	1447	100	100
-5	1440	100	100
-4	1434	100	100
-3	1427	100	100
-2	1421	100	100
-1	1414	100	100
0	1408	100	100

X. Conclusion

The Cassini spacecraft performed exactly as expected throughout all 22 orbits of the proximal mission. In many ways, the Cassini spacecraft performance actually exceeded expectations. To protect the spacecraft from potential high dust environment, Cassini was commanded to point its HGA towards the dust RAM direction as a shield to protect the rest of its sensitive instruments. However, the dust environment turned out to be so benign that one of the already uplinked HGA-to-RAM attitude during periapsis crossing was actually superseded at the last minute in order to get better sampling of the dust. The spacecraft control authority also met its expectations. No contingency “pop-up” or “pop-down” maneuvers were necessary. During the final plunge, the RCS thrusters performed so well against the Saturn atmospheric drag torque that the spacecraft actually held on to 3 more seconds of telemetry before the spacecraft tumbled, in comparison to the original prediction using current Saturn atmosphere models. Radiation effects on the spacecraft hardware such as the IRU and the SSRs were minimal. Although Saturn and its rings displayed greater interferences to the SRU than ever seen before, normal procedures were used to mitigate the bright body interferences and to select safe mode attitudes. Similarly, normal procedures were used to implement live vector updates to account for the pointing dispersions caused by trajectory deviations against the reference. Fault scenarios were simulated but were ultimately not needed. In the end, the Cassini operations team was well prepared for the proximal orbit mission. No flight software or ground software modifications were required, no special operational procedures were implemented, and the onboard fault protection settings did not need to be changed.

The Grand Finale mission was not like any other missions ever flown. For the first time, a spacecraft flew close to Saturn and explored the space between Saturn and its innermost rings. The rich science results left behind by the Cassini spacecraft were unprecedented. The science community will be analyzing the results for many years, or even decades, to come.

Acknowledgement

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